Optical Sky Brightness at Cerro Tololo Inter-American Observatory from 1992 to 2006[1]

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ABSTRACT

We present optical (*UBVRI*) sky brightness measures from 1992 through 2006. The data are based on CCD imagery obtained with the CTIO 0.9-m, 1.3-m, and 1.5-m telescopes. The *B*- and *V*-band data are in reasonable agreement with measurements previously made at Mauna Kea, though on the basis of a small number of images per year there are discrepancies for the years 1992 through 1994. Our CCD-based data are not significantly different than values obtained at Cerro Paranal. We find that the yearly averages of *V*-band sky brightness are best correlated with the 10.7-cm solar flux taken 5 days prior to the sky brightness measures. This implies an average speed of 350 km s^{-1} for the solar wind. While we can measure an enhancement of the night sky levels over La Serena 10 degrees above the horizon, at elevation angles above 45 degrees we find no evidence that the night sky brightness at Cerro Tololo is affected by artificial light of nearby towns and cities.

Subject headings: Astronomical Phenomena and Seeing

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1. Introduction

A knowledge of the sky background is fundamental to optical and infrared observational astronomy. The accuracy of photometric measurements hinges on the signal-to-noise *ratio*, so we would like the noise to be as small as possible. The noise has a number of components, among them the dark counts (or dark current), the readout noise, the sky background, and the cosmic ray flux. Furthermore, an instrument must be matched to the typical seeing at a given site, and that stipulates an optimum pixel size for a digital detector. For existing sites and all planned facilities we want to know: 1) the site quality; 2) what kind of natural atmospheric variations there are on short time scales and long time scales; and 3) whether population growth in the area is affecting the astronomical site quality. Another issue we will emphasize in this paper is that of telescope baffling. If a telescope is poorly baffled, then skylight is scattered around the inside of the telescope, raising the background against which we are trying to measure faint astronomical targets. Not much can be done for old telescopes, but this is a critical issue for the design and commissioning of new telescopes.

The literature on the subject of sky brightness is quite large and continues to grow. In particular, the reader is directed to Roach & Gordon (1973), Leinert et al. (1998), and references therein. Data obtained at specific sites are described by Walker (1988), Pilachowski et al. (1989), Krisciunas (1997, hereafter K97), Benn & Ellison (1998), Patat (2003), and Patat (2007).

Rayleigh (1928) and Rayleigh & Jones (1935) were the first to note a possible correlation between the sky brightness and the solar cycle. See Walker (1988) for a more detailed discussion. There are, of course, different measures of solar activity. Walker (1988, Fig. 4) shows a reasonably strong correlation between the V- and B-band sky brightness as a function of the 10.7-cm solar flux.[8] K97, Fig. 3, shows a good correlation of the zenith V-band sky brightness vs. the 10.7-cm solar flux if we eliminate data from the years 1985 and 1993 from the analysis. It is not too surprising that there is a correlation of the V-band sky brightness and some measure of the solar activity. The solar wind energizes the Earth's upper atmosphere, causing occasional auroral displays. A much smaller effect is the nightly airglow, which has the same origin. The strong atmospheric emission line at 557.7 nm, attributed to [O I], falls in the V-band.[9] While this line contributes directly to V-band

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[8]The units of the solar flux are $10^{-22}/m^2/Hz$. For this paper we obtained the 10.7-cm solar flux values from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/. These are the "Observed, Series C" data from Penticton, British Columbia.

[9]We note that the Sloan Digital Sky Survey's g' and r' bands are strategically chosen so that the 557.7 nm line falls in between their response curves (Fukugita et al. 1996).

sky brightness, the solar flux must also contribute to B-band sky brightness variations. K97 found that the color of the sky was quite constant over the course of the solar cycle, with $\langle B - V \rangle = 0.930 \pm 0.018$.

In this paper we discuss 15 years of sky brightness measures obtained at Cerro Tololo Inter-American Observatory. The data were obtained with CCD detectors on the CTIO 0.9-m, 1.3-m, and 1.5-m telescopes. The 0.9-m and 1.5-m telescopes were built in the late 1960's, so are no longer modern telescopes. The 1.3-m telescope was originally used for the Two Micron All Sky Survey (2MASS). Following the conclusion of that survey the 1.3-m was transferred to CTIO, and, along with the 0.9-m, 1.0-m, and 1.5-m telescopes, became part of the Small and Moderate Aperture Research Telescope System (SMARTS) in 2003. Preliminary analysis of the CTIO data was discussed by Vera et al. (2002).

2. Deriving the Sky Brightness

Our CCD-based data were reduced within the IRAF[10] environment. First the images are bias-corrected, trimmed, and flattened. The 0.9-m images are typically read out with four amplifiers, which have different effective gains, but the resulting flattened frames show no significant background differences in the four quadrants. To calibrate the sky brightness data on any given night we used 3 to 10 standards of Landolt (1992).

Using DOPHOT or DAOPHOT it is possible to determine the point spread function (PSF) of the telescope and CCD camera for every frame, then, using this information, subtract the stars, galaxies, and cosmic rays from the frames. We did *not* do this. Instead, using some IRAF scripts written by one of us (NBS), we simply made use of the IMHIST program. Since a majority of the pixels are looking at sky, the mode of the pixel counts will correspond to the sky level.[11] After iteratively clipping low and high pixels, we fit a Gaussian function to the remainder of the data in the histogram. The peak of this Gaussian fit gives us the most robust value of the number of counts in the sky. Of course, one assumes that the master bias frame and overscan regions used for bias correction remove the bias without the addition of any significant systematic effect. Any problems with bias subtraction can be essentially

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[10]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA, Inc. under cooperative agreement with the National Science Foundation.

[11]We carried out tests with imagery of two globular clusters and found that our IRAF scripts gave nearly identical sky brightness values compared to those obtained using IMSTAT on small sub-areas or deriving the median sky counts in a sky annulus while doing aperture photometry on more isolated stars at the edges of the fields.

eliminated by deriving the sky brightness from frames having long exposures (e.g. 300 sec or longer).

Say we perform large aperture photometry on a standard star using APPHOT within IRAF, and this gives us a total of $C_\star$ counts above sky with an exposure time of $E_\star$. The standard star is observed at airmass $X_\star$. The atmospheric extinction in that band (either assumed or derived) is k_λ. Let the standard magnitude of the star from Landolt (1992) be $M_\star$. Let C_{sky} be equal to the mean sky counts times the area of the software aperture in a *different* image with exposure time E_{sky}. Following Eq. 1 of K97, the magnitude of the sky signal is then

$$S \ = \ -2.5 \log \, (C_{sky}/C_\star) + 2.5 \log \, (E_{sky}/E_\star) + k_\lambda X_\star + M_\star \ . \tag{1}$$

One assumes that there are no systematic errors in the exposure times as given by the data acquisition system. Obviously, tests can and should be done to investigate this question. The basic rule is: longer exposures are better.

Since the catalogue value of the standard star magnitude corresponds to its out-of-atmosphere value, one corrects the standard star signal for the extinction in the Earth's atmosphere by adding the term $k_\lambda X_\star$. The sky brightness along some line of sight in the sky is *not* corrected to an out-of-atmosphere value. Given the plate scale of the CCD image (i.e., the number of arc seconds per pixel), we can calculate the area of the software aperture A, measured in square arc seconds. The sky brightness $I(\mu)$ in magnitudes per square arc second is then

$$I(\mu) \ = \ S \ + \ 2.5 \log \, A \ . \tag{2}$$

Of course, one can also fit a PSF to the standard stars to obtain the number of counts above sky. The corresponding apparent magnitude of a sky patch can directly be transformed into the sky brightness in magnitudes per square arc second by knowing the plate scale and calculating the area of the sky patch. Finally, one can use measurements of multiple standard stars to give a more robust calibration of the sky flux. Since the sky has the color of a K0-type star, one should avoid blue standard stars in order to eliminate as much as possible any filter effects.

Because magnitudes are a logarithmic system, for statistical purposes it is not correct to average sky brightness values in mag/sec^2. One should convert the data to some kind of flux units, average them, then convert the numbers back to mag/sec^2. Following Garstang (1989), Schaefer (1990), and K97, for the *V*- and *B*-bands one can use nanoLamberts for the

flux:

$$B_{obs}(\text{nL}) \; = \; 0.263 \; a^{[Q-I(\mu)]} \; , \tag{3}$$

where $a = (100)^{0.2} \approx 2.51189$, $Q = 10.0 + 2.5 \log(3600^2) \approx 27.78151$, $I(\mu)$ is the sky brightness in mag/sec^2, and the factor 0.263 is the surface brightness (in nL) of a star with $V = 10$ spread out over one square degree.

For airmass less than 1.6 (and possibly larger) it is appropriate to correct the observed sky brightness to the zenith value using Eq. 1 of Schaefer (1990):

$$B_{zen} \; = \; B_{obs}/(1 \; + \; Z_{rad}^2/2) \; , \tag{4}$$

where Z_{rad} is the zenith angle in *radians*.

As noted above, the CTIO 0.9-m and 1.5-m telescopes are 40 years old. Our analysis shows that the CTIO 1.3-m telescope gives, on average, demonstrably fainter sky brightness values compared to data from the two much older telescopes. After some simple experiments in the dome, we attribute this to bad baffling in the older telescopes. The bottom line is that the camera window facing the Cassegrain secondary mirror should only receive light from that secondary. A poorly baffled telescope will allow light scattering off the inside of a solid telescope tube to hit the CCD camera window. This will brighten the sky background. A poorly baffled telescope with an open tube will allow light from the sky *and* light from the inside of the dome to degrade the measured sky brightness.

Using imagery obtained with the three telescopes during 2003, 2004, and 2005, we have derived baffle corrections for the data obtained with the 0.9-m and 1.5-m telescopes (Table 1).[12] We assume explicitly that the more modern CTIO 1.3-m telescope is well baffled and the sky brightness values from images obtained with it are correct.

Note that the baffle corrections increase monotonically with wavelength, reaching half a magnitude in the *I*-band. If there were other factors contributing to systematic errors in our CTIO data from 1992 through 2002, it would be difficult to determine at this stage.

Finally, we note that the *U*-band baffling corrections for the older telescopes are inconsistent with the *BVRI* corrections, in the sense that they equal -0.27 mag/sec^2 for the

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[12]This is to say that the baffle corrections are adjustments for systematic errors in the 0.9-m and 1.5-m data. These adjustments could have systematic errors of their own, which we estimate to be of order $\pm$ 0.05 mag/sec^2.

0.9-m and 0.00 mag/sec^2 for the 1.5-m. If bad baffling is the cause of the arithmetically positive corrections for the other filters, then it does not make sense that the CCD camera on the 1.3-m would suffer local light pollution only in the U filter.

3. A Sanity Check on Systematic Errors

As a sanity check, we shipped to Chile the photometer and telescope used by K97 for his sky brightness measures obtained at Mauna Kea from 1985 through 1996 (Krisciunas 1996). That system gives an elliptical footprint on the sky of 6.522 ± 0.184 square arc minutes and uses an RCA 931A photomultiplier tube. Given the nature of this instrument, it was difficult to avoid stars fainter than V = 13 in the beam. Ironically, poor tracking allowed us to sample a small swath of sky and pick off the minimum sky signal. We would expect that CCD-based sky brightness values would be somewhat fainter than data obtained with the Krisciunas system, since faint stars and galaxies can be eliminated from CCD analysis.

In Tables 2 and 3 we give some sky brightness values obtained on two photometric nights at CTIO in December of 2006.[13] Table 2 gives data obtained with the CTIO 0.9-m telescope. Some of the V-band sky brightness values were obtained within two hours of the end of astronomical twilight (which occurred at roughly 01:16 UT on those nights). The other CCD data were obtained at a fixed location on the sky, RA = 5 hours, DEC = −30 degrees. Table 3 gives data obtained with the Krisciunas system at a number of positions west of the celestial meridian on the very same nights.

Fig. 1 shows the sky brightness measures obtained at CTIO with the two different systems on 2006 December 23 and 24 UT. Clearly, there is evidence that the sky continued to get darker long after the nominal end of astronomical twilight. We shall consider only the data obtained more than two hours after the end of astronomical twilight. In the V- and B-bands, respectively, the data from the Krisciunas system are, on average, 0.13 and 0.17 mag/sec^2 brighter than the baffle-corrected 0.9-m data. These differences can be attributed to a combination of factors: 1) uncertainty in the beam size of the Krisciunas system; 2) the unknown contribution of faint stars in the Krisciunas system beam; and 3) systematic

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[13]Landolt (1992) fields were observed in $BVRI$ on 7 occasions over the course of 2006 December 23 and 24. Using EVALFIT within the PHOTCAL package, we found that the RMS uncertainties of the $BVRI$ magnitudes of the standards were between ± 0.01 and ± 0.02 mag on these nights. Extinction values were measured to ± 0.01 mag/airmass. Thus, we judge these two nights to be of excellent photometric quality. For the calibration of the single channel photometer data our principal standard stars were BS 1179 and ζ Cae. Our check star was ρ For. Their B and V magnitudes were obtained from Hoffleit & Jaschek (1982).

errors in the baffling corrections for the 0.9-m. On the whole, however, the data obtained with the Krisciunas system and the 0.9-m are in reasonable agreement because one would expect the single channel photomutipler tube data to give brighter values than CCD data based on pixels that were free of the light of stars and galaxies.

We note that the recent data obtained with the Krisciunas system (corrected to the zenith) give $\langle B - V \rangle = 0.906 \pm 0.034$, while the data from the 0.9-m obtained on the same two nights (and more than two hours after the end of astronomical twilight) give $\langle B - V \rangle = 0.951 \pm 0.013$. These values are in good agreement with the average from K97 of $\langle B - V \rangle = 0.930 \pm 0.018$.

On 2006 December 23 and 24 we also measured the sky brightness at 10 to 11 degrees above the left flank of La Serena.[14] In Figs. 4 and 5 of Garstang (1989) we find the results of his modelling the atmosphere at Boulder, Colorado (elevation 1655 m), and Mt. Graham, Arizona (elevation 3267 m).[15] Since CTIO is 2215 m above sea level, it makes sense to average the two models for our purposes here. We note, however, that the continental air of the United States is not as aerosol-free as the maritime air of CTIO. We assume that the total contribution to the V-band sky brightness from directly transmitted light, Rayleigh scattering, and aerosol scattering is 1.94 times brighter at a zenith angle of 79 or 80 degrees compared to the contribution at the zenith. For Garstang's Boulder model the value is 1.84 and for Mt. Graham the value is 2.03. In Table 4 we convert some of our data from Table 3 to fluxes in nL and compare the observed fluxes at high airmass with what we would predict on the basis of the mean zenith sky brightness scaled by the factor from Garstang's model.

Luginbuhl (2007, private communication) indicates that on one recent occasion he and his colleagues measured the sky brightness near Flagstaff, Arizona, to be $V = 21.85$ mag/sec^2 at the zenith and 21.21 mag/sec^2 at elevation angle 10 degrees. Those numbers translate into a flux ratio of 1.80. Whether for CTIO the most robust value of this parameter is 1.8 or 2.0, we observed ≈ 3 times as much flux at high zenith angle compared to the zenith.

From the summit of Cerro Tololo one can look down at La Serena, Vicuña, and Andacollo and see artificial light with the naked eye if those locations are not covered by cloud. Statistically speaking, we obtained the *same* values of the sky brightness at very high airmass on December 23 and 24. At 10 to 11 degrees above the left flank of La Serena we measured enhancements of 72 and 44 percent in the V-band on the two nights in question. These are

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[14]We could not aim directly over the center of the city because the dome of the 0.9-m telescope was in the way.

[15]A careful reading of the text of Garstang's paper reveals that the captions to his Figs. 4 and 5 should be swapped.

almost certainly measurements of light pollution attributable to La Serena. At elevation angles of 45 degrees or higher there is no measurable effect on the night sky brightness at Tololo at this time.

4. A Database of Useful CTIO Sky Brightness Measures

Over the course of years of observing galaxies that have hosted supernovae, we have accumulated many images. These images can be used for the measurement of the sky brightness at Cerro Tololo. Of course, these images were taken under a variety of sky conditions: photometric, non-photometric, with and without moonlight. Some are short exposures. Some are long exposures. Some were taken during twilight or when the zodiacal light was still strong. Some were taken in the middle of the night.

Our database of images usable for measurement of the sky brightness involved an extensive selection process to reduce the effects of artifical brighteners of the sky. This includes:

1. Removal of images with exposure times shorter than 10 seconds. Given the huge number of pixels in a CCD chip, we find that it *is* possible to get reliable sky brightness readings with exposures as short as 10 seconds.

2. Removal of images with airmass greater than 1.6. The effect of dust and particles in the Earth's atmosphere begins to dominate the sky brightness levels closer to the horizon. See Garstang (1989, Figs. 4, 5). Limiting the study to low airmasses reduces the effect of these particles on the sky brightness values.

3. Removal of images taken within 30 degrees of the Galactic plane. Any image of the night sky will contain countless unresolved sources which brighten the level of the sky. By excluding images taken in the Galactic plane we significantly decrease the number of unresolved stars that could contribute to this brightening.

4. We include only images taken more than two hours after the end of evening astronomical twilight (i.e. Sun 18 degrees below the horizon) until two hours before the start of morning astronomical twilight. During astronomical twilight the sky is being brightened by the Sun. Up to two hours after the end of evening astronomical twilight and starting two hours before the start of morning astronomical twilight the sky is partially illuminated by the zodiacal light, which is sunlight scattering off interplanetary dust.

5. Removal of images taken when the Moon was above the horizon or if the Moon was within 30 minutes of the horizon.

6. Removal of images taken on non-photometric nights. Any clouds would have a significant impact on the observed brightness levels. We consulted the historic sky conditions from the CTIO website and excluded nights known to be non-photometric.

7. Removal of images more than three standard deviations from the mean on those nights when multiple images were obtained.

8. For reasons outlined above, we choose to consider only U-band values obtained with the CTIO 1.3-m telescope.

In Table 5 we give the yearly averages of the $BVRI$ sky brightness at CTIO. Many of these yearly averages, especially during the 1990's, are based on a small number of images per year. Of course, many other observers were using the CTIO 0.9-m and 1.5-m telescopes. We should have organized a system whereby observers could copy to disk deep images obtained in the middle of the night, along with images of standard stars. The Paranal database described by Patat (2007) is understandably more extensive than ours described here.

As mentioned above, it is not correct to average data in magnitudes or mag/sec² because those are logarithmic units. One should convert to fluxes, average the fluxes, and then convert the average back to magnitude units if one so chooses. This is what we have done in our analysis.

Fig. 2 shows the individual zenith V-band sky brightness values derived from CCD imagery obtained at CTIO. While a solar cycle effect is apparent, we feel that yearly averages show the effect more clearly.

Fig. 3 shows the yearly averages from K97 along with the CTIO yearly averages. There is an overlap of four years. As first reported by Vera et al. (2002), the CTIO data of 1992 to 1994 are noticeably fainter than the data obtained at the 2800-m level of Mauna Kea and reported by K97. Even if we correct the Mauna Kea data of 1992 for the difference of solar flux levels of the nights in question, we cannot reconcile the numbers. The CTIO V-band data of 1992 are based on 3 nights, so we could just be dealing with small number statistics. Perhaps the baffle corrections obtained from imagery of 2003 to 2005 are not the correct values to apply to the data of 1992 through 1994. The small amount of data obtained in 1996 at the two locations matches within the errors, and the sanity check described in §3 of this paper is reasonable assurance that under careful conditions we get comparable values with the single channel system and the CCD camera on the 0.9-m at CTIO.

In Fig. 4 we show the yearly averages of the BRI sky brightness at Mauna Kea and at CTIO. The Mauna Kea B-band data alone show a solar cycle effect, as does the CTIO B-band dataset taken on its own. However, as in the V-band, there is a serious discrepancy

as to zeropoint in the years 1992 to 1994. We see no evidence for a solar cycle effect in the R- and I-band data from CTIO.

Grand averages of CTIO and Paranal data are given in Table 6. The Paranal data are based on images taken from April 2001 through April 2006 (Patat 2007). Thus, both datasets cover years of solar maximum and solar minimum. However, the years 2001 through 2006 are not equally represented in the Paranal data. There are more observations from 2001 to 2003 when the Sun was more active. Patat (2007, private communication) indicates that the long term B- and V-band sky brightness at Paranal is roughly 0.1 mag/sec^2 fainter than the values in Table 6.

In Table 6 the uncertainties given are the standard deviations of the *distributions*, not the standard deviations of the means. Statistically speaking, the Paranal data and the CTIO data are in agreement, given the typical standard deviations of $\pm$ 0.20 mag/sec^2. With the 0.1 mag/sec^2 adjustment mentioned above, the CTIO data are, on average, 0.06 mag/sec^2 fainter than Paranal in B but *equal* in V. This is evidence that our baffling corrections are close to being correct, for these bands at least.

Under the reasonable assumption of a physical cause and effect between activity on the Sun and the chemical reactions occurring in the Earth's atmosphere which result in the airglow, we naturally ask: is this due to the light which shines on the Earth eight minutes after leaving the Sun's photosphere? Or is it due to the solar wind, i.e. to particles coming from the Sun?

In Fig. 5 we plot the yearly averages from Table 5, converted to flux, vs. the mean of the 10.7-m solar flux 4.5 days prior to when the sky brightness was measured. We made various versions of this plot using solar flux values from the day prior to a given night's observations until 8 days prior. Since the solar flux is measured about 0.5 d prior to a given night's observations, this corresponds to $-8.5 \leq \Delta\,\mathrm{T} \leq -0.5$ d. We find a minimum reduced χ^2 value at $\Delta\mathrm{T} = -5.0$ d. Given the mean distance of the Earth from the Sun, a time delay of 5.0 days corresponds to a mean speed of the solar wind of ≈ 350 km s^{-1}.

This can be compared to the escape speed at the surface of the Sun, 618 km s^{-1}, and to the speeds of the leading edges of coronal mass ejections, namely 450 km s^{-1} at solar maximum, and 160 km s^{-1} at solar minimum (Kahler 2000). More extensive photometry and sky spectra obtained at Paranal may shed light on this time delay effect.[16]

As shown by Walker (1988), Pilachowski et al. (1989), and K97, on any given night the

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[16]From http://solarscience.msfc.nasa.gov/SolarWind.shtml we can see a graph of the solar wind velocity over the previous seven days. A mean speed of 400 km s^{-1} is quoted, with a range of 300 to 800 km s^{-1}.

sky brightness can vary 10 to 50 percent. There is not one *single* value for any given night. Whole-night wide-angle digital movies of the sky at CTIO obtained by Roger Smith show bands of OH emission passing over the summit on time scales of tens of minutes. It is not surprising to measure variations of the airglow component of the sky brightness.

5. Discussion

Photometry of astronomical point sources in sparse fields is easy. Photometry of stars in crowded fields is more difficult. Photometry of extended sources is much more difficult because one must worry about seeing, contrast against the sky, and plate scale. Photometry of the night sky is of intermediate difficulty. The biggest systematic uncertainties arise from certain aspects of CCD observing that we normally do not worry about: accuracy of exposure times, imperfect bias subtraction, light leaks, and bad baffling in the telescopes.

Ideally, one would like to be able to measure large solid angles of the sky and to calibrate the observed sky brightness by means of many identifiable standard stars. Such a system has been implemented, and is described by Duriscoe, Luginbuhl, & Moore (2007). These authors are able to image the entire sky over a span of half an hour and can obtain robust photometric zeropoints and extinctions from the identification and detection of over 100 bright standard stars in each dataset.

A comparison of sky brightness obtained with different equipment is largely a search for systematic errors. Because of the importance of northern Chile to ground based observational astronomy, we felt it was important to calibrate the night sky at Cerro Tololo using images easily available to us. This also involved taking data with the very same telescope and photometer used by Krisciunas (1997) for an 11 year study at Mauna Kea. We find that observations obtained at CTIO with the Krisciunas system are consistent with observations obtained with the CTIO 0.9-m telescope if we adopt corrections for bad baffling in that telescope.

We have used an extensive database of images obtained for supernova research and have whittled down the size of the database by excluding observations on non-photometric nights, observations taken within two hours of the end or beginning of astronomical twilight, observations when the Moon was within 30 minutes of the horizon, images obtained within 30 degrees of the Galactic plane, and images taken at airmass greater than 1.6. The resulting database demonstrates a correlation of the V-band sky brightness with the phase of the solar cycle, as has been found by others over the past 80 years. A solar cycle effect can be seen to a lesser extent in the B-band data, but there appears to be no significant solar cycle effect

in the R- and I-band data.

We find that the V-band sky brightness is most tightly correlated with the solar flux obtained 5 days prior to the night in question. This corresponds to a mean speed of ≈ 350 km s^{-1} for the solar wind, in the mid-range of velocities of coronal mass ejections at solar minimum and solar maximum.

We find no evidence of light pollution at Cerro Tololo within 45 degrees of the zenith at this time. However, 10 degrees over La Serena we measured a 58 ± 14 percent enchancement of the V-band sky brightness on two nights.

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Table 1.   Baffle Corrections[a]

Telescope	B	V	R	I
0.9-m	0.269	0.274	0.369	0.521
1.5-m	0.132	0.286	0.322	0.527

[a]The values in the table are the number of magnitudes per square arc second to *add* to the raw sky brightness data to eliminate systematic differences in sky brightness compared to the CTIO 1.3-m telescope. These values are based on data taken during the years 2003 through 2005.

Table 2.   Sky Brightness Values from CTIO 0.9-m Imagery[a]

UT Date	⟨UT⟩	RA	DEC	Filter	Exptime	Observed	Z	Corrected
Dec 23	01:07	23:36:39	$-10°15'$	V	300	21.262	44.83	21.552
Dec 23	01:35	00:14:08	$-10\ 25$	V	300	21.591	42.80	21.858
Dec 23	02:06	02:08:18	$-3\ 50$	V	300	21.933	32.50	22.095
Dec 23	03:00	02:20:38	$-7\ 54$	V	300	21.948	36.15	22.145
Dec 23	04:08	05:00:00	$-30\ 00$	V	400	22.160	6.58	22.167
Dec 23	04:42	05:00:00	$-30\ 00$	V	400	22.171	15.90	22.212
Dec 23	05:05	05:00:00	$-30\ 00$	V	400	22.124	18.83	22.181
Dec 23	04:00	05:00:00	$-30\ 00$	B	600	23.081	4.91	23.085
Dec 23	04:34	05:00:00	$-30\ 00$	B	600	23.072	12.23	23.096
Dec 23	04:56	05:00:00	$-30\ 00$	B	600	23.053	17.16	23.101
Dec 24	01:05	23:29:44	$-9\ 37$	V	300	20.857	47.05	21.173
Dec 24	01:31	00:28:38	$+0\ 21$	V	300	21.241	46.75	21.553
Dec 24	01:58	02:20:37	$-9\ 24$	V	300	21.742	25.58	21.845
Dec 24	02:54	02:08:18	$-3\ 50$	V	300	21.503	40.92	21.750
Dec 24	03:53	05:00:00	$-30\ 00$	V	400	21.939	4.16	21.942
Dec 24	04:13	05:00:00	$-30\ 00$	V	400	21.971	8.35	21.982
Dec 24	04:32	05:00:00	$-30\ 00$	V	400	22.012	12.49	22.037
Dec 24	04:53	05:00:00	$-30\ 00$	V	400	22.045	17.08	22.092
Dec 24	05:11	05:00:00	$-30\ 00$	V	400	22.011	20.99	22.082
Dec 24	05:30	05:00:00	$-30\ 00$	V	400	21.977	24.94	22.075
Dec 24	05:49	05:00:00	$-30\ 00$	V	400	21.960	29.12	22.092
Dec 24	06:07	05:00:00	$-30\ 00$	V	400	21.920	33.03	22.087
Dec 24	03:44	05:00:00	$-30\ 00$	B	600	22.991	2.49	22.992
Dec 24	04:04	05:00:00	$-30\ 00$	B	600	22.898	6.68	22.905
Dec 24	04:23	05:00:00	$-30\ 00$	B	600	22.952	10.81	22.990
Dec 24	04:44	05:00:00	$-30\ 00$	B	600	22.978	15.42	23.017
Dec 24	05:02	05:00:00	$-30\ 00$	B	600	22.991	19.32	23.051
Dec 24	05:21	05:00:00	$-30\ 00$	B	600	22.968	23.28	23.054
Dec 24	05:40	05:00:00	$-30\ 00$	B	600	22.937	27.46	23.055
Dec 24	05:58	05:00:00	$-30\ 00$	B	600	22.916	31.38	23.068

[a]Year is 2006. UT is in hours and minutes. Right ascension is in hours, minutes, seconds (J2000). Declination is in degrees and arc minutes. Exposure times are in seconds. Column 7 is observed sky brightness in mag/sec^2, using baffling corrections from Table 1. Z is the zenith angle in degrees. Column 9 data in mag/sec^2 are values from column 7, corrected to the zenith using Eq. 4.

Table 3. CTIO Sky Brightness Values from Single Channel System[a]

UT Date	$\langle$UT$\rangle$	RA	DEC	Filter	Observed	Z	Corrected
Dec 23	04:28	04:40	-30	V	22.038 (0.06)	15.34	22.076 (0.06)
Dec 23	04:47	01:50	$+18$	V	20.761 (0.04)	78.54	$\cdots$
Dec 23	05:15	05:00	-30	V	21.992 (0.06)	21.18	22.064 (0.06)
Dec 23	04:38	04:40	-30	B	22.893 (0.10)	17.50	22.943 (0.10)
Dec 23	04:45	01:50	$+18$	B	22.266 (0.06)	78.92	$\cdots$
Dec 23	05:18	05:00	-30	B	22.884 (0.10)	21.83	22.960 (0.10)
Dec 24	05:00	05:00	-30	V	21.747 (0.06)	18.79	21.804 (0.06)
Dec 24	05:10	02:10	$+17$	V	20.782 (0.04)	79.67	$\cdots$
Dec 24	05:24	04:12	-5	V	21.657 (0.06)	45.11	21.950 (0.06)
Dec 24	05:47	05:00	-30	V	21.801 (0.06)	28.91	21.951 (0.06)
Dec 24	05:00	05:00	-30	B	22.750 (0.10)	18.79	22.807 (0.10)
Dec 24	05:12	02:10	$+17$	B	22.290 (0.06)	80.06	$\cdots$
Dec 24	05:22	04:12	-5	B	22.618 (0.10)	44.72	22.907 (0.10)
Dec 24	05:44	05:00	-30	B	22.634 (0.10)	28.27	22.759 (0.10)

[a]Year is 2006. UT and right ascension are in hours and minutes. Declination is in degrees. Column 6 is observed sky brightness in mag/sec^2. Z is the zenith angle in degrees. Column 8 data in mag/sec^2 are values from column 6, corrected to the zenith using Eq. 4. Values in parentheses are estimated random errors.

Table 4.   Detection of Artificial Light at High Zenith Angle[a]

UT Date	Filter	B_{zen}(nL)	B_{obs}(nL)	Ratio(obs/zen)	B_{pred}(nL)	Ratio(obs/pred)
Dec 23	V	50.7	169.1	3.34	98.4	1.72
Dec 23	B	22.5	42.3	1.88	$\cdots$	$\cdots$
Dec 24	V	59.6	165.9	2.78	115.6	1.44
Dec 24	B	25.3	41.4	1.64	$\cdots$	$\cdots$

[a]Year is 2006. The values in column 6 are equal to the values in column 3 times 1.94. This scaling factor is obtained from averaging models of one lower elevation site and one higher elevation site from Figs. 4 and 5 of Garstang (1989) and corresponds to a zenith angle of 79 to 80 degrees.

Table 5.   Yearly Averages of Sky Brightness at CTIO[a]

Year	$\langle B \rangle$	N_B	$\langle V \rangle$	N_V	$\langle R \rangle$	N_R	$\langle I \rangle$	N_I
1992	22.971 (0.024)	3	21.842 (0.056)	5	$\cdots$	$\cdots$	$\cdots$	$\cdots$
1993	23.122 (0.085)	2	21.897	1	$\cdots$	$\cdots$	$\cdots$	$\cdots$
1994	23.259 (0.022)	5	22.034 (0.012)	4	$\cdots$	$\cdots$	$\cdots$	$\cdots$
1996	22.964 (0.050)	2	21.904 (0.005)	2	$\cdots$	$\cdots$	19.956	1
1997	22.745 (0.057)	11	21.803 (0.051)	15	$\cdots$	$\cdots$	$\cdots$	$\cdots$
1998	22.982 (0.074)	3	21.911 (0.018)	4	$\cdots$	$\cdots$	$\cdots$	$\cdots$
1999	22.741 (0.018)	13	21.600 (0.039)	11	$\cdots$	$\cdots$	$\cdots$	$\cdots$
2000	22.766 (0.048)	8	21.564 (0.055)	11	20.880	1	19.374	1
2001	22.870 (0.024)	11	21.668 (0.052)	15	21.110 (0.190)	3	19.828(0.172)	5
2002	22.676 (0.067)	10	21.694 (0.045)	13	21.162 (0.067)	13	19.895 (0.061)	18
2003	22.815 (0.028)	42	21.817 (0.020)	78	21.208 (0.018)	65	19.814 (0.032)	71
2004	22.772 (0.025)	49	21.710 (0.024)	63	21.085 (0.019)	60	19.848 (0.035)	57
2005	22.834 (0.026)	38	21.854 (0.024)	95	21.278 (0.022)	83	19.866 (0.021)	95
2006	22.994 (0.032)	13	22.061 (0.031)	12	21.018 (0.003)	2	19.726 (0.032)	2

[a]Values are measured in mag/sec^2. The numbers in parentheses are 1-σ uncertainties (mean errors of the mean). There are no data from 1995. N_i is the number of images, not the number of nights.

Table 6.   Mean Sky Brightness at CTIO and Paranal[a]

Site	$\langle U \rangle$	N_U	$\langle B \rangle$	N_B	$\langle V \rangle$	N_V	$\langle R \rangle$	N_R	$\langle I \rangle$	N_I
CTIO	22.12 (0.19)	27	22.82 (0.19)	210	21.79 (0.22)	329	21.19 (0.19)	227	19.85 (0.25)	250
Paranal	22.35 (0.19)	261	22.66 (0.16)	1332	21.69 (0.21)	1619	20.91 (0.23)	3595	19.65 (0.28)	2882
difference	−0.23	$\cdots$	0.16	$\cdots$	0.10	$\cdots$	0.28	$\cdots$	0.20	$\cdots$

[a]Sky brightness is measured in mag/sec^2. U-band average from CTIO is from images taken with the 1.3-m telescope only. Paranal values from Patat (2007) are based on data from April 2001 through April 2006, but the Paranal averages are weighted more toward 2001 to 2003, when the solar cycle was closer to maximum. The values in parentheses are the standard deviations of the *distributions*, not the standard deviations of the means.

Fig. 1.— Values of sky brightness from CTIO. Top panels: V-band sky brightness. Bottom panels: B-band sky brightness. Left panels: data of 2006 December 23 UT. Right panels: data of 2006 December 24 UT. The blue dots are data from the CTIO 0.9-m reflector. The green squares are data obtained with the single channel system of Krisciunas (1996). All data have been corrected to the zenith.

Fig. 2.— Upper panel: Individual CCD-based values of zenith V-band sky brightness from CTIO. Lower panel: 10.7-cm solar flux.

Fig. 3.— Upper panel: Data obtained at the 2800-m level of Mauna Kea using a 15-cm telescope and single channel photometer (Krisciunas 1996), along with the average of the data obtained at CTIO in December of 2006 (green squares). These data were typically taken within 20 degrees of the zenith. The blue dots are yearly averages of data obtained at CTIO using CCD imagery. The CTIO data and the single channel data from December 2006 have all been reduced to the zenith. Lower panel: 10.7-cm solar flux.

Fig. 4.— Yearly averages of BRI sky brightness. In the top panel the squares represent data from K97, along with the data from Table 3 of this paper. Circles represent CCD-based data from CTIO presented in this paper.
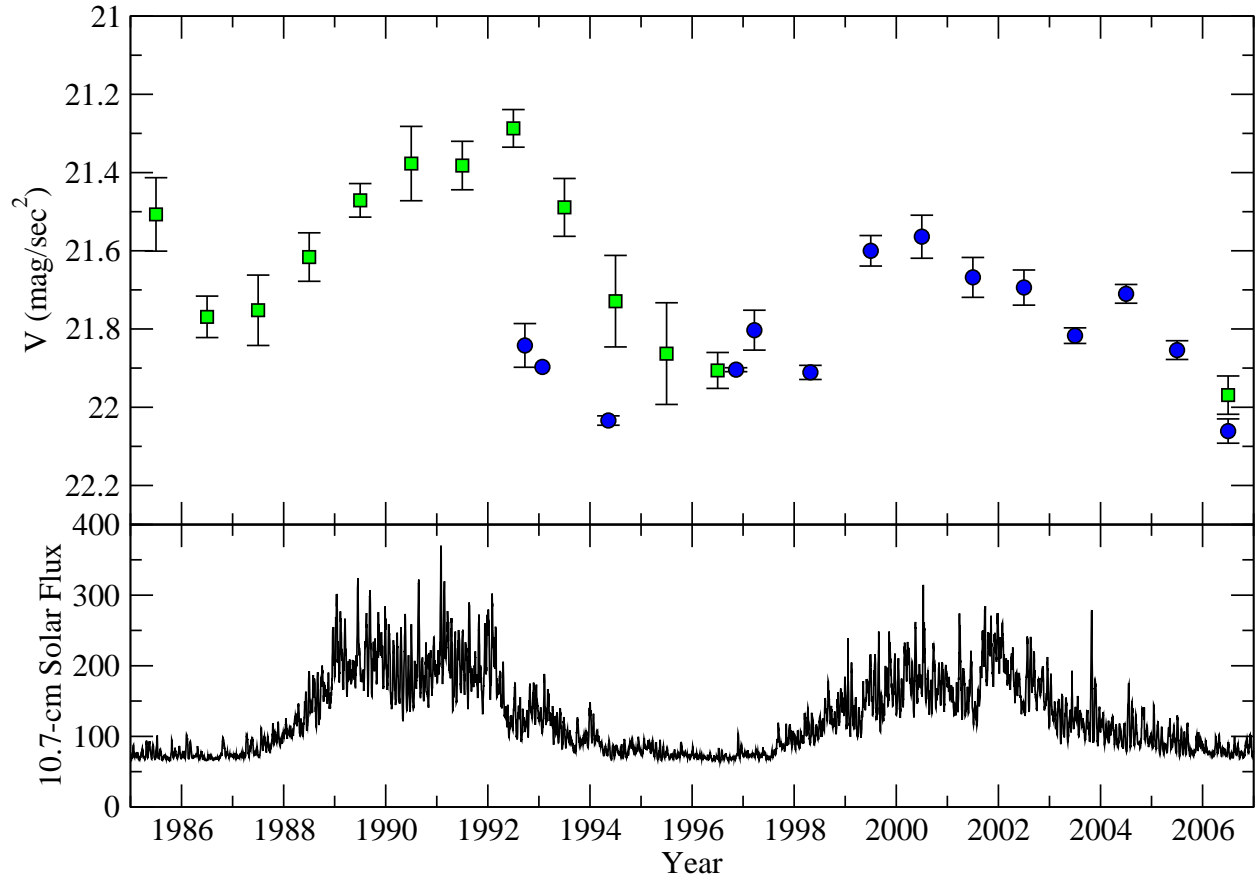
Fig. 5.— Yearly averages of zenith V-band sky brightness obtained from CCD imagery at Cerro Tololo (converted to flux) vs. the average of the 10.7-cm solar flux 4.5 days prior to when the sky brightness was measured.
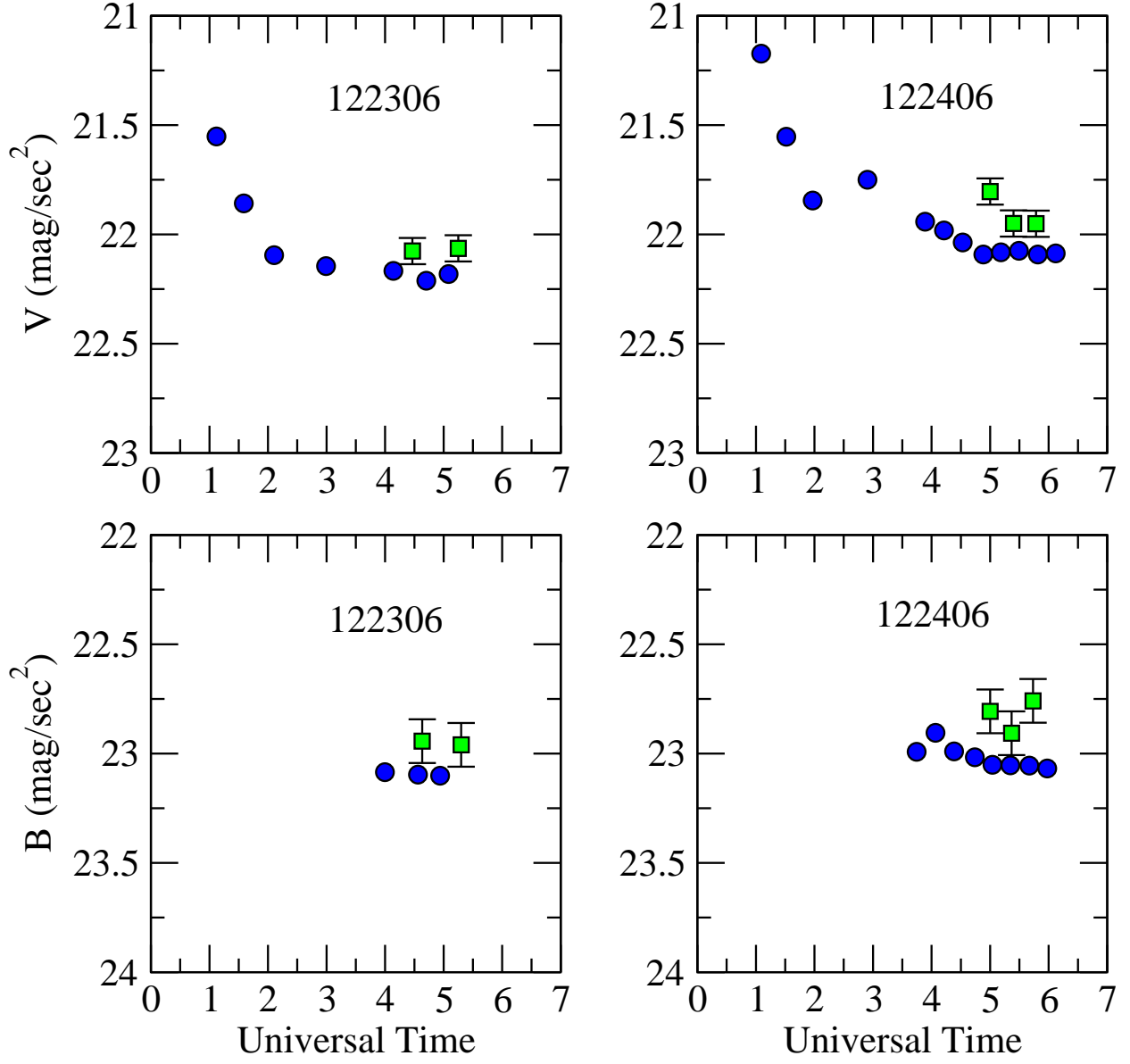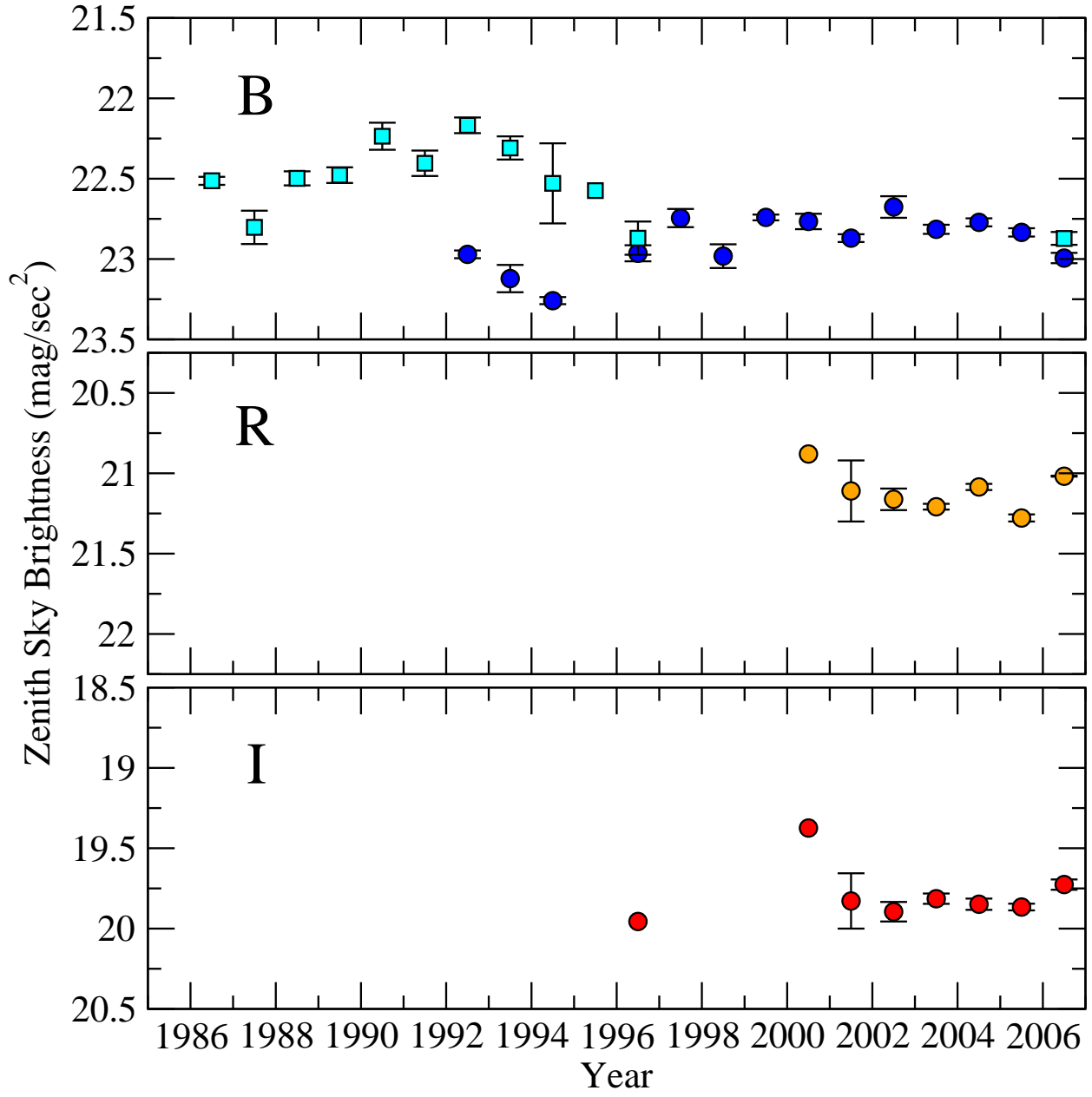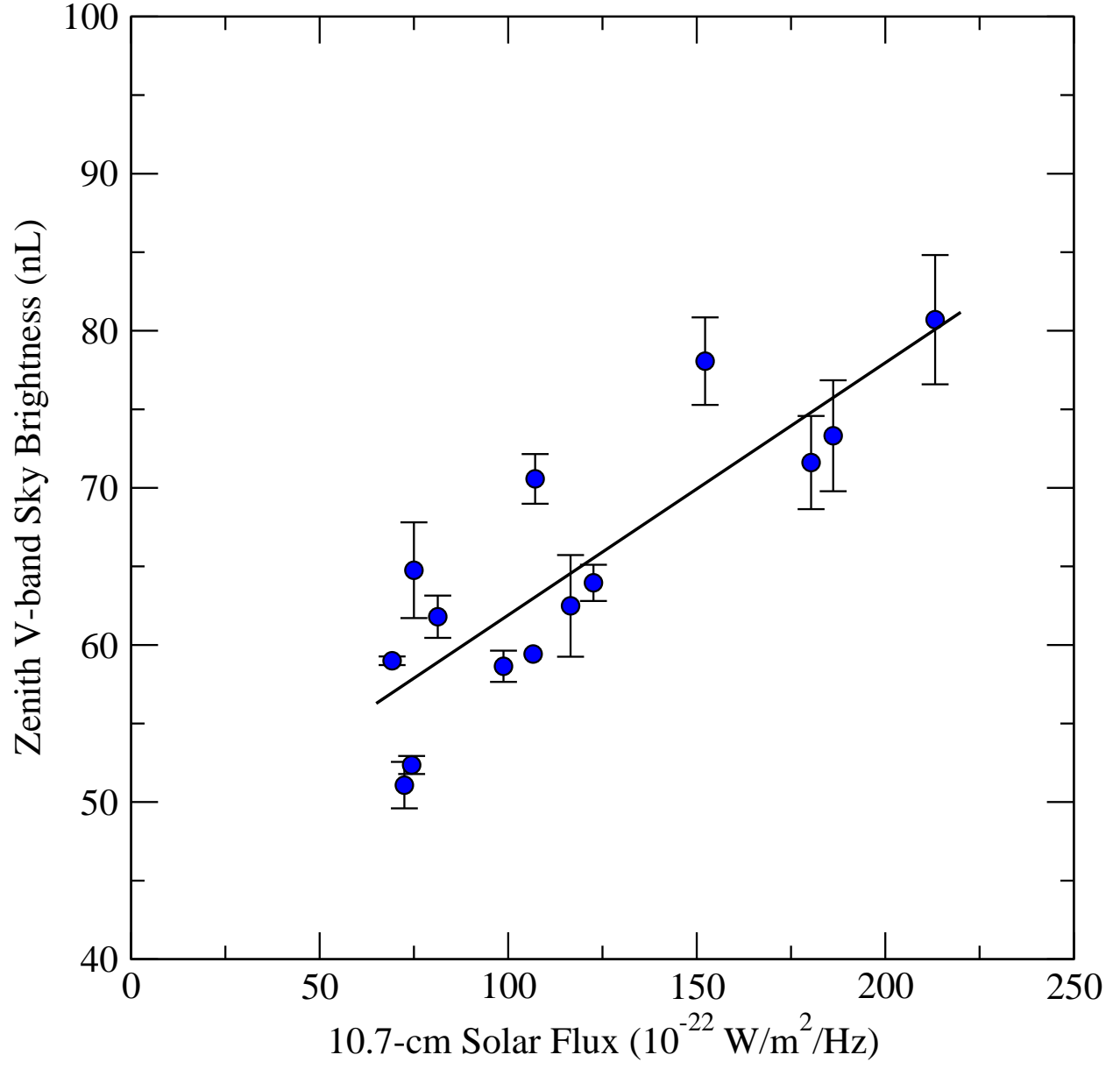
Krisciunas *et al.* Fig. 1
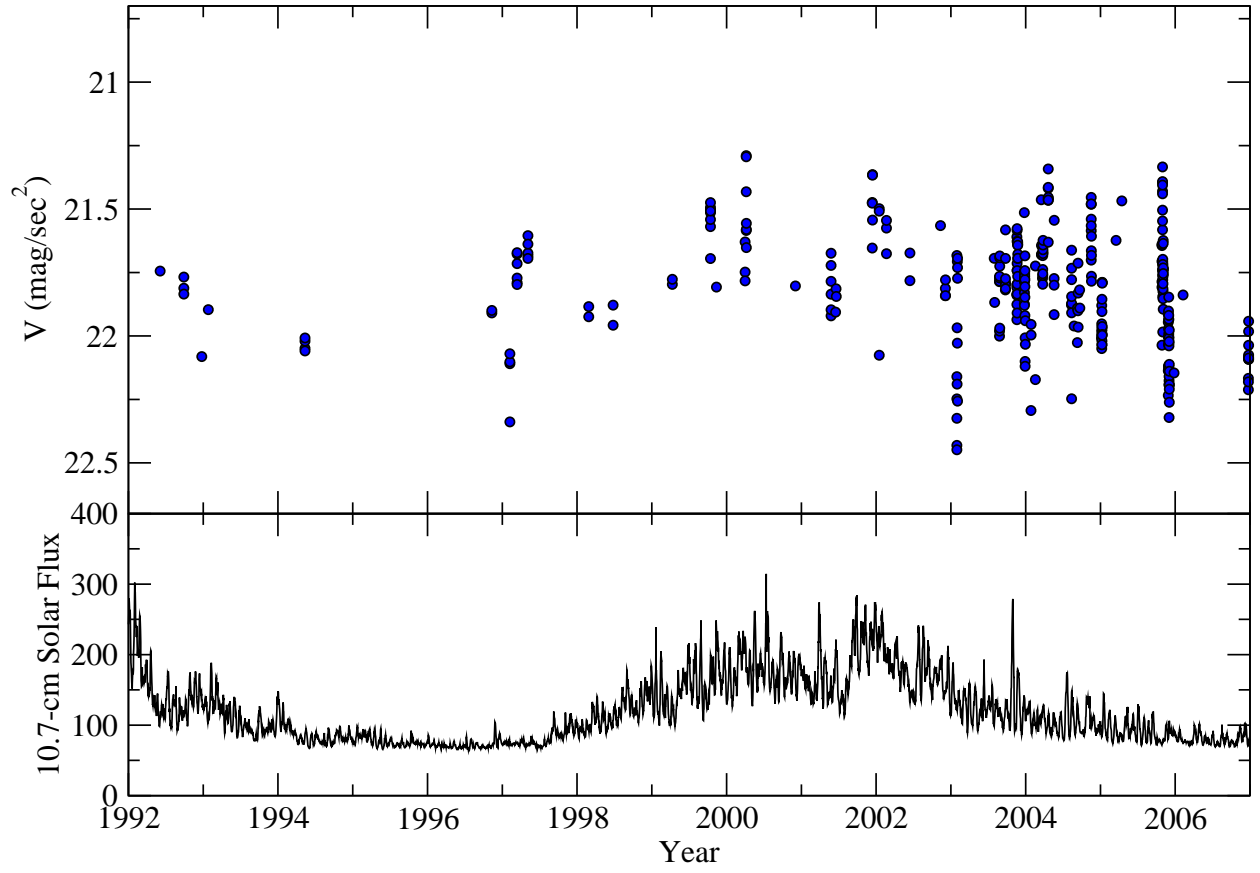
Krisciunas *et al.* Fig. 2

Krisciunas *et al.* Fig. 3

Krisciunas *et al.* Fig. 4

Krisciunas *et al.* Fig. 5